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HEAT EXCHANGERS WITH PERFORATED PLATES
IZMENJIVAČI TOPLOTE SA PERFORIRANIM PLOČAMA

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ABSTRACT

Heat exchangers with perforated plates are not newness (Babic), but it is not wide adopted solution. However, the arrangement and size of perforations affect its efficiency. Indications that the efficiency could be increased by more than 20% were obtained by computer simulation of heat exchanger of similar structure. This is sufficient reason to continue and expand the investigation of such heat exchangers. In this paper is presented preliminary laboratory experimental research of newly designed heat exchanger. The aim is primarily to qualitatively and quantitatively verify the positive results obtained and indicated by the computer simulation. A final goal is to establish the optimal operating regime of heat exchanger in a wider range of expected state of working fluids and possible variations of heat exchanger construction. Further research will move in the direction of computer modeling of the similar heat exchanger which is far simpler, faster and cheaper, using software package STAR CCM+.

Key words: *heat exchanger, efficiency, heat transfer.*

REZIME

Izmenjivač toplote sa perforiranim pločama nije novost (Babic) ali nije ni masovno prihvaćeno rešenje. Raspored i dimenzije perforacija utiču na njegovu efiksanost, ali način i veličina uticaja još nisu u potpunosti ispitani. Računarskom simulacijom izmenjivača slične konstrukcije dobijene su naznake da bi efikasnost mogla da bude veća za više od 20%. Ovo je dovoljan razlog da se nastave i prošire ispitivanja ovakvih izmenjivača toplote. Ovde se daju rezultati laboratorijskog istraživanja sa ciljem da se kvalitativno i kvantitativno provere i potvrde pozitivni rezultati dobijeni i nagovešteni računarskom simulacijom. Kao konačni cilj, želja autora je da utvrde optimalani režimi rada izmenjivača u širem opsegu očekivanih stanja radnih fluida i mogućih varijacija konstrukcije izmenjivača. Dalja istraživanja kretaće se u pravcu računarskog modelovanja identičnog izmenjivača pomoću softverskog paketa STAR CCM+, koje je daleko jednostavnije, brže i jeftinije. Već razvijeno i provereno postrojenje biće takođe korišćeno za verifikaciju novih rašunarski modelovanih optimalnih odnosa geometrijskih i strujnih parametara konstrukcije.

Ključne reči: *izmenjivač toplote, efikasnost, prenos toplote.*

INTRODUCTION

The basic equation for heat transfer from the solid surface to fluid (or vice versa)

$$Q = \left(\overline{h}A\right)\overline{\Delta T}\,, \qquad (1)$$

where Q is heat capacity (heat transfer rate) delivered to a specific weight of fluid, indicates that in order to increase heat transfer rate it is necessary to increase some of the parameters or more of them: the heat transfer coefficient h (i.e. $\overline{h}$), area A or temperature difference $\overline{\Delta T} = \overline{T_s - T_f}$. All researches, including the latest trends, are oriented towards increasing the heat transfer coefficient and heat exchange surface, in short - the so-called exchanger size $\overline{h}A$. This led to a decrease of the channels through which fluids flow in a heat exchanger and the emergence of new classification of heat exchangers (*Kandlikar et al.,2003; Mehendale et al., 2000*).

The exchanger that is the subject of experimental research, according to the classification (*Kandlikar et al., 2003*) belongs to the exchangers with mini channels formed as narrow fin passages (*Mehendale et al., 2000*). The increased intensity of heat transfer, manifested by increasing of h (or $\overline{h}$) implies a reduction of A (reducing heat exchanger size), which ultimately leads to high compactness of exchangers (high power (capacity) per unit volume of exchanger) - undoubtedly expand the area of application.

Layout and dimensions of the perforations in perforated plate heat exchanger influence to its efficiency. Computer simulation, performed with the software package STAR CCM+, showed that the heat transfer efficiency of common finned tube exchanger with forced air flow can be increased if the fins are used in a different way. Comparing the finned tube and perforated plates heat exchangers, it was obtained that the efficiency of heat exchanger was as much as 44% higher in favor of the exchanger with perforated plates, while the water and air flow were the same (*Ilin, 2010*). However, the problem of increased pressure drop through perforated plate at water side appears. Therefore, the simulations with reduced water flow were carried out. Tenfold reduction in the water flow has resulted in a hundredfold reduction in pressure drop. The air flow was not changed. For in this way obtained parameters efficiency of heat exchanger with perforations was 40% higher than for the finned tube exchanger. This was reason enough to continue and expand the investigation of such heat exchangers. In this paper is presented the preliminary laboratory research of newly-designed heat exchangers. The ultimate goal of this research is to qualitatively and quantitatively verify the positive results obtained and implied by the computer simulation. Below are shown the first results of measurements and are indicated the potential problems and directions for further research.

Nomenclature

A (m^2)	- surface
h (J/(m^{2}K)	– convection heat transfer coefficient
$\dot{m}$ (kg/s)	- mass flow rate
p (Pa)	- pressure
Q (W)	- heat transfer rate
T (K)	- temperature
$\dot{V}$ (m^3/s)	- volumetric flow rate
v (m/s)	- velocity
Symbols	
Δ	- change of parameter value

∞ - ambient

Subscripts

a - air

ave - average

f - fluid

i - inlet

o - outlet

s - surface

w - water

Overscripts

\- - averaged

MATHERIAL AND METHOD

Description of heat exchanger

Considered heat exchanger (*Fig. 1*) consists of 6 plates, 2 mm thick with perforations 2 mm in diameter with axial distance of 3.5 mm. The plates are identical and stacked at a distance of 1 mm, slightly dispached, so that when fluid flows, it passes through the perforations and hits the next plate, and then goes through a perforation in it and so on (*Fig. 2*). The heating fluid is warm water (about 60 °C), and heated fluid is air. Both fluids pass through the perforated plates, each at its side of exchanger. The flow arrangement in exchanger is cross-flow (Figure 2).

Fig. 1. Heat exchanger with perforated plates

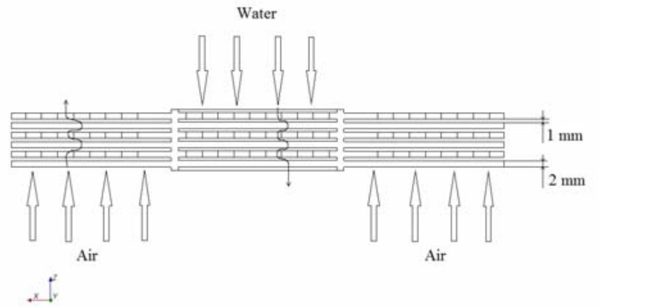

Fig. 2. Schematic of cross-flow through heat exchanger

Heat transfer rate

In the steady (stationary) mode, each exchanger without mixing of fluids an energy balance equation is valid:

$$0 = \dot{Q}_w - \dot{Q}_a \,. \tag{2}$$

Under the usual assumptions about flow through the channels of the exchanger (neglected changes of kinetic and potential energy of both flows, the specific heat of both fluids are constant), exchanged heat capacity (Q_w and Q_a) are:

$$Q_w = \dot{m}_w \cdot c_w \cdot \Delta T_w \,, \tag{3}$$

$$Q_a = \dot{m}_a \cdot c_a \cdot \Delta T_a \,, \tag{4}$$

where : $\dot{m}$ - mass flow rate (kg/s), *c* - specific heat (J/kgK), ΔT - temperature difference of fluid between inlet and outlet section (K).

Violation of Eq. (2) in the conducted measurements indicates unsteady regime or errors in the control and measurement of certain parameters. At the same time, Eq. (1) is still valid.

Exergy Transfer Effectiveness

This parameter allows comparison of different heat exchangers, as well as optimization of the specific heat exchanger. According to the literature (*Wu et al., 2007*) effectiveness exergy transfer is easier to define, and enables the same as the heat transfer effectiveness. It can be defined as

$$\varepsilon_e = \frac{AETR}{MPETR} \tag{5}$$

where: AETR - actual exergy transfer rate of objective medium, MPETR - maximum possible exergy transfer rate of objective medium.

For heat exchangers operating at temperatures above ambient temperature and with a certain final pressure drop, exergy transfer effectiveness the air side is (*Wu et al., 2007*)

$$\varepsilon_{e,a} = \frac{T_{ao} - T_{ai} - T_\infty \ln \dfrac{T_{ao}}{T_{ai}} - \dfrac{I \Delta p_a}{c_{pa}}}{T_{wi} - T_{ai} - T_\infty \ln \dfrac{T_{wi}}{T_{ci}}} \tag{6}$$

where $I = \dfrac{T_\infty R}{p_{ai}}$ for ideal gas (air, in this case).

Exergy transfer effectiveness of the water side can be also from (*Wu et al., 2007*), where $I=\rho$ for incompressible fluid (water).

EXPERIMANTAL INVESTIGATION

Experimental investigation of heat exchanger characteristics was conducted in the Laboratory of Fluid Mechanics at the Faculty of Technical Sciences in Novi Sad.

Experimental apparatus

Th fig. 3 shows a schematic layout of the test laboratory facilities. The plant consists of heat exchanger, fan, pump, water heater (tank with heater), deaeration tank, piping and measuring equipment. Heated fluid is air and cooled fluid is water. Heat exchanger is made of aluminum.

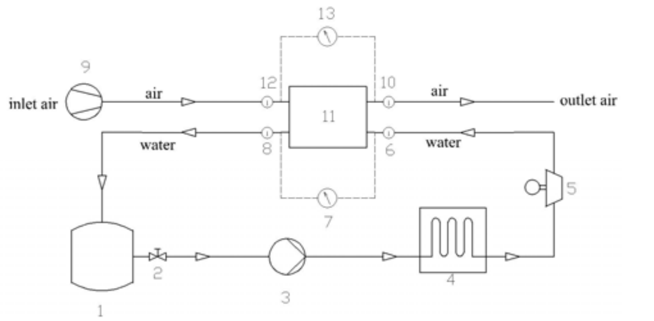

Fig. 3. Scheme of experimental apparatus (1-deaeration reservoir; 2-valve; 3-pump; 4-tank with heater; 5-flow meter; 6-inlet water temperature measuring; 7-water pressure drop measuring; 8-outlet water temperature measuring; 9-fen; 10-outlet air temperature measuring; 11-heat exchanger; 12-inlet air temperature measuring; 13- air pressure drop measuring)

The test facility (*Fig. 3*) can be divided into two parts: water and air. Water part is composed of the reservoir, circulator pump, tank with heater and piping. Aerial part consists of the fan and piping. Air and water, heated and heating fluid, flow through a heat exchanger. Both at the water and the air are measured: the temperature at the inlet and outlet heat exchanger, flow and pressure drop through the heat exchanger. The test facility is adapted to possibilities of the flow and temperature change at both parts, air and water.

Experimental method

Experimental measurements were conducted after the establishment of steady state, i.e. fluctuation (variation) of temperature was within ± 0.1 °C at the entrance and exit, as defined by (*Paeng et al., 2009*). To establish a steady state took several hours. In order to gain preliminary results, authors were of the opinion that the temperature difference can be higher in order to obtain preliminary results, and because of the long time required to achieve steady state (*Fig. 4*). The water is heated in the tank (power of heater 2.5 kW, t_{max} = 65 °C). After that a pump with maximum flow (0.071 l/s) is turned on. Hot water in the pipeline, flows through the measuring device (Coriolis flow and temperature meter), heat exchanger, enters the reservoir to deaerate, then the pipeline, pump and goes into the tank with a heater. The air is transported by fans with regulated flow through pipeline to the heat exchanger, passes through a heat exchanger, heats up and releases through the outlet pipe into the room. Air velocity is measured at the outlet pipe using a hot wire anemometer (Testo 425). Velocity profile is measured according to standards in order to define average velocity. After that is defined volumetric flow (*D*=150 mm). Thermocouples were placed on water and the air side and were used to measure temperatures at the inlets and outlets of the heat exchanger. Pressure drop through the heat exchanger at both air and water sides were measured by differential manometers.

During the experiment following parameters were measured:

- Air temperature at the inlet of the fan,
- Air temperature at the outlet of the exhaust pipe from the heat exchanger,
- Water temperature at the inlet of the exchanger,
- Water temperature at the outlet of the exchanger,
- Ambient temperature,
- Water flow rate,
- Air velocity at the outlet of the exhaust pipe from the heat exchanger,
- Atmospheric pressure,
- Pressure drop through the heat exchanger at the water side,
- Pressure drop through the heat exchanger at the air side.

RESULTS AND DISCUSION

Experimental Results

Five measurements were carried out. The results are presented in a *table 1*.

Table 1 Heat transfer rate on water and air side

No.	t_{amb} [°C]	fluid	$\dot{V}$ [l/s]	Δp [Pa]	t_i [°C]	t_o [°C]	P [W]	$\frac{P_a}{P_w}\cdot 100\%$	ε_{ea}
1	21.85	air	118.44	25	13.5	26.4	1798.62	91,4	0.0439
		water	0.0711	107.7	50	43.35	1967.76		
2	21.5	air	119.77	23	12.5	29	2327.45	78,6	0.0341
		water	0.0711	103	60.1	50.1	2959.64		
3	22.6	air	117.44	23	11.5	26.8	2106.09	85,5	-0.0361
		water	0.0711	103.5	55.92	47.6	2461.92		
4	23.8	air	21.5	3	13.13	37.2	586.83	49,7	0.1258
		water	0.0711	105.3	60.43	56.44	1180.67		
5	18.01	air	27.2	4	11.4	34.45	717.31	64,3	0.2189
		water	0.0711	104	57.06	53.29	1115.56		

Steady state at the water side according to (*Paeng et al., 2009*) is reached when the difference in temperature at the inlet and outlet of the exchanger is less than 0.1 °C. In this case it was after 75 minutes, (*Fig. 4*). It is interesting to see that the inlet and outlet temperature difference was in the range of 3.72 °C to 3.88 °C (*Fig. 5*), which shows that, from the point of transferred heat, process can be considered steady from the moment of turning the fan on. For example, one can see, that for the water flow rate of 0.071 l/s and air of 0.0217 m3/s, water inlet temperature was 60.43 °C, and outlet 56.44 °C, i.e. temperature difference was 3.99 °C. Inlet air temperature was 8 °C, and heated air was 44.5 °C (Table 1, measuring 4).

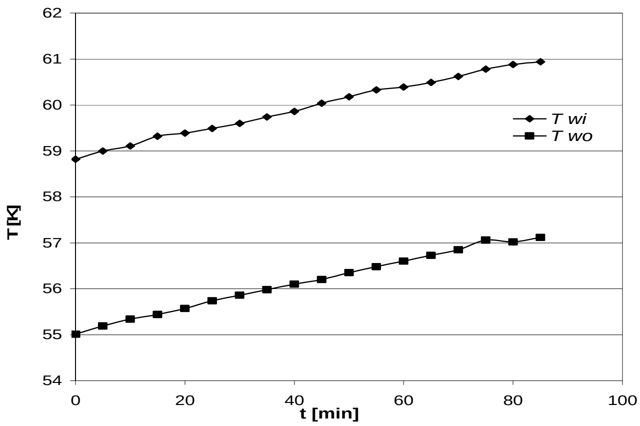

Fig. 4 Temperature change of water at the inlet and outlet of the heat exchanger in the period before establishing steady state

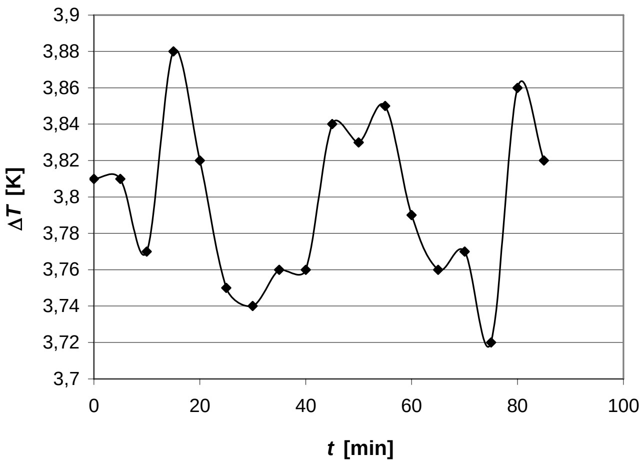

Fig. 5 Change of water temperature difference at the inlet and outlet of the heat exchanger

DISCUSSION

It can be seen that heat transferred to the water side and heat received by air are not equal. This may be due to poor measuring, above all air temperature at the inlet and outlet of the heat exchanger, as well as not achieved steady state. Achieving steady state proved to be a major problem. The authors suspect that 75 minutes is sufficient to achieve steady state. Heat exchanger surface is very large with large quantity of material; therefore the device is very inert. Diversity of gained results suggests that it should insist on reaching the small fluctuations in temperature at the inlet and outlet of both fluids and only then declare that the steady state is achieved. Another problem may be the lack of isolation, although the great attention was paid to it. For the further investigations some changes in apparatus should be made, like insertion of heaters in deaeration reservoir and thus remove the tank with heater. This will provide possibility to have higher flow rates, allowing measurements at different water flow rates, too.It is necessary to perform computer modeling of the presented heat exchanger in order to compare measured values and those calculated by computer simulation. In that way, further investigations would be carried out by computer modeling. According to preliminary results, the effectiveness of the device is greater when the air flow is lower. Power transferred from water to air is less than the power of the heater used to heat water. For higher air flows more heat is transferred. Further research will try to determine the heat transfer effectiveness, or better, as recommended in the literature (*Wu et al., 2007*), exergy transfer effectiveness which is defined by Eq. (5) that can easily be determined utilizing a method based on the exergy transfer effectiveness in a given inlet and outlet temperature of the heat exchanger.

CONCLUSION

This paper presents preliminary laboratory testing of newly-designed heat exchangers with perforated plates. In order to obtain reliable results of measurements it is necessary to perform correction of the experimental apparatus. It is necessary to increase the strength of the heater that it would be possible to work with higher water temperatures. The existing fan would be desirable to replace with the less noisy one and with less power. In order to allow variation of the flow of water it is necessary to set pump of higher power. Temperature measurements should be done automatically, every 5-10 minutes. When the temperature fluctuations at the inlet and outlet are less than 0.1 °C (*Paeng et al., 2009*), it should be considered that steady state is achieved and, only after that, perform measurements. To achieve steady state requires longer time, and only then can be expected even result. It is necessary to keep the number of effective parameters to a minimum. Whenever possible, do more measurements with a constant temperature at the inlet.

As a final goal, the desire of authors is to determine optimal regimes of heat exchanger in a wider range of expected state of working fluids and possible variations in the design of exchanger. Further research will move in the direction of computer modeling of the same heat exchanger in software package STAR CCM+, which is far simpler, faster and cheaper. Already developed and tested plant will be used for verification of new computer modeled optimal geometry and flow parameters of the structure.

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